Comments on "A Heat Balance for the Bering Sea Ice Edge"

LAKSHMI H. KANTHA
Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ 08542

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Hendricks et al. (1985) have carried out a heat budget calculation for the Bering Sea marginal ice zone for midwinter conditions, using observational data from the MIZEX West (1983) study. During the midwinter period, the ice cover on the Bering Sea Shelf reaches its southernmost extent, which is roughly the shelf break, and remains more or less stationary till the onset of spring retreat. The ice is continually formed in the northern portions of the shelf and advected southward by northeasterly winds toward the ice edge, where it melts. The principal cause of this melting is the northward advection of warm Pacific waters onto the ice edge. A strong two-layer stratification exists under the ice, with colder but fresher water overlying warmer but saltier waters—a condition conductive to double-diffusive convection. The ice edge is associated with a strong thermal front.

The authors concluded that the melting of ice advected southward in the marginal ice zone (MIZ) at a rate of about 0.2 m s^{-1} requires a heat of roughly 27 MW per meter of ice edge and that the heat loss to the atmosphere through the leads in the ice cover amounts to about 13 MW m^{-1}. The northward advection of heat into the mixed layer under ice by warmer water masses to the south provides about 26 MW m^{-1}. Although uncertainties with these estimates are large, on the order of 50% or so, overall, this leaves a deficit of about 14 MW m^{-1}. To account for this deficit, the authors invoke double-diffusive processes to transport about 8 MW m^{-1} from the warmer lower layer to the layer under ice. The lateral diffusion across the ice-edge front is shown to amount to about 1 MW m^{-1} (see their Table 3).

However, the authors dismiss the possibility of vertical transport of heat from the lower to the upper layer by mechanical mixing because of the strong pycnocline. They appear to conclude that the relevant Richardson number is too large for shear instabilities and, therefore, for shear-induced mixing to be important. This conclusion does not appear to be justified, as indicated below.

Laboratory experiments (e.g., see Moore and Long, 1971; Kantha et al., 1977) have shown that in a stably stratified two-layer system with shear across the interface, the interface is kept sharp by shear-induced turbulence even at high values of the relevant bulk Richardson number Ri. In Moore and Long's experiment, Ri is defined as $D\Delta b/(\Delta u)^2$, where D is the depth of each layer, Δb the buoyancy difference across the interface, and Δu the velocity difference. In their experiment, the layers were driven in opposite directions by means of jets to produce shear at the interface. Moore and Long showed that a buoyancy transport exists across the interface, due to turbulent entrainment processes at the interface, at all values of Ri. They discovered that this transport can be written as $q = C_1(\Delta u \Delta b)\,\mathrm{Ri}^{-1}$ and is valid for Ri values as high as 40. This relation is equivalent to a Ri^{-1} dependence for the equivalent tubulent entrainment velocity u_e:

$$\frac{u_e}{\Delta u} \sim C_1\,\mathrm{Ri}^{-1}.$$

The value of C_1 is 8×10^{-4} according to Moore and Long (1971).

Thus, not only does the interface remain sharp under the action of the shear at the interface at all Richardson numbers, but there is a nonnegligible buoyancy transport across as well, so as to continually decrease the buoyancy difference across the interface with time. These entrainment results can be extrapolated to the case of the MIZ, since it can be shown that the presence of rotation (nonzero Coriolis parameter) has negligible influence on the entrainment rates for the parameter range of interest to the MIZ.

The pycnocline under the ice is definitely sharp, indicating strong turbulence in both layers. Part of this turbulence energy is undoubtedly due to convection in the two layers driven by the double-diffusive transport of heat across the pycnocline. However, a substantial part must also be due to mechanical mixing. The dominant source of mechanical mixing is the shear across the interface. Although the lack of reliability of the current meter data from the rotor-type meters, deployed at all but the near-surface mooring points, makes it harder, due to wave pumping and biofouling (Muench and Schumacher, 1985), to estimate the velocities in the lower layer and therefore the shear across the interface, the authors' own estimates (Hendricks et al., 1985, p. 1752) suggest a difference in velocity of about 0.2 m s^{-1} between the two layers. If one takes a conservative estimate of about half this value, 0.1 m s^{-1} for Δu, 50 m for D, and

3×10^{-3} m s^{-2} for Δb, the value of Ri $\sim$ 15 and therefore $u_e \sim 5 \times 10^{-6}$ m s^{-1}. Assuming this average value for the entrainment velocity across the entire marginal ice zone, the vertical heat flux across the pycnocline due to shear-induced mechanical mixing is given by

$$Q_M = \rho l u_e C_p \Delta T,$$

where ΔT is the temperature difference between the layers and l is the width of the MIZ. Assuming a conservative value of 1.0°C for ΔT (actual value $\sim$ 2°–2.5°C) and $l \sim$ 100 km, $Q_M \sim$ 2.10 MW m^{-1}. This value is comparable to the lateral diffusive transport across the ice edge thermal front.

The value of Q_M depends critically, of course, on the shear across the interface, namely the value of ΔU. We assumed a conservative value of 0.1 m s^{-1} for ΔU. If we assume, however, the higher value of 0.2 m s^{-1} that appears to be suggested by the authors (Hendricks et al., 1985, p. 1752), u_e is eight times larger and therefore $Q_M \sim$ 16 MW m^{-1}, a value larger than the vertical double-diffusive transport estimated by the authors. The values deduced here are essentially rather rough estimates based on the information available from the authors' paper and extrapolation of laboratory results. They nevertheless make the essential point, viz., the vertical transport of heat across the pycnocline due to mechanical mixing is not negligible and ranges in importance between the lateral diffusive transport and the vertical double-diffusive transport.

Mechanical mixing, more often than not, coexists with double-diffusive mixing in the ocean, a fact well recognized by workers dealing with double-diffusive processes (Linden, 1974; Crapper, 1976, for example). Crapper (1976) considered explicitly the transport across a diffusive interface such as that studied by Marmorino and Caldwell (1976) but in the presence of turbulence imposed externally by an oscillating grid. He has shown (see also Linden, 1974) that the total flux across the interface can be split into two components, one a diffusive flux due directly to double-diffusive instability and the second an entrainment flux due to mechanical mixing. This means that mechanical mixing does not affect double-diffusive mixing and vice versa. This is plausible if the turbulence energies in the two cases are widely separated in spectral space. Since mechanical mixing in this case is due to an ensemble of relatively infrequent mixing episodes, the spectral gap hypothesis appears to be well justified. This hypothesis is also often invoked in dealing with turbulence in the atmospheric and oceanic mixed layers due to the simultaneous presence of shear and convective mixing. The present situation also consists of a combination of convective (driven albeit by double-diffusion) and mechanical mixing at the interface, the latter once again due to relatively infrequent mixing episodes, presumably due to sporadic shear instabilities of the interface. There are no experiments dealing with the simultaneous presence of double-diffusive convection and shear across the interface, to the author's knowledge, and therefore no clues exist as to the contributions of each to the buoyancy transfer across the interface. Nevertheless, if we assume the vertical transport of heat due to mechanical mixing to be simply additive to the double-diffusive vertical transport, this adds anywhere from 2 to 16 MW m^{-1} to the heat source terms (see Table 3, Hendricks et al., 1985), thus bringing the source and sink terms into a closer balance. This is significant in spite of the large uncertainties associated with the estimates of each individual term.

There is yet another way to approach the problem of estimating the vertical transport across the interface due to mechanical mixing, based on the turbulence intensity in the mixed layer near the entraining buoyancy interface. The region close to the shelf break of the Bering Sea Shelf is stirred rather energetically by strong tidal motions, principally the diurnal K_1 component (Mofjeld, 1986) with some contribution from the semidiurnal M_2 (see Hendricks et al., 1985). The bottom layer is therefore well mixed by tidal action. The upper layer is, in its turn, kept well mixed by the turbulence generated by the ice motion. An ice velocity of 0.2 m s^{-1} is roughly equivalent to a friction velocity u_* of about 10^{-2} m s^{-1}.

The entrainment processes at a buoyancy interface due to turbulent motions generated by an applied shear stress have been investigated in the laboratory by Kato and Phillips (1969) and Kantha et al. (1977), using a rotating screen to apply a surface stress to a stratified fluid in an annulus. The results of these experiments as well as those of other investigators such as Scranton and Lindberg (1983), Jones and Mulhearn (1983) and Deardorff and Willis (1982) provide some clues to the question of parameterization of the entrainment rate. For the most part, an approximate relation based on the bulk Richardson number Ri$_*$ defined as $D\Delta b/u_*^2$ can be used to characterize the entrainment rate, even though it appears that the curvature effects in the annulus cast some doubt on the validity of extension of these results to the field (Scranton and Lindberg 1983; Deardorff and Yoon, 1984). However, recent experiments in a racetrack-shaped flume by Narimousa et al. (1986) show that the entrainment results are roughly in agreement with those of Kantha et al. (1977), at least at values of Ri$_*$ less than about 800. For higher values, the stabilizing effects of curvature near the inner (convex) wall in Kantha et al.'s experiments lead to lower values for the entrainment rate than Narimousa et al.'s experiments.

Once again using these laboratory experiments on shear-driven entrainment as a guide, the entrainment velocity u_e can be written as

$$\frac{u_e}{u_*} \sim f(\mathrm{Ri}_*).$$

Using values of 50 m for D, 3×10^{-3} m s^{-2} for Δb, and 10^{-2} m s^{-1} for u_*, Ri$_*$ $\sim$ 1500 and u_e/u_* is conservatively at least 10^{-3} (from Narimousa et al., 1986; see also Kantha et al., 1977). Therefore, u_e turns out to be about 10^{-5} m s^{-1} and Q_M is 4.0 MW m^{-1}.

Note that unless there is turbulence in the lower layer also, the entrainment driven by turbulence in the upper layer would lead to deepening of the upper and shallowing of the bottom layer. Since observations suggest that the pycnocline remains roughly stationary in the vertical direction, the turbulence in the lower layer must be strong enough to compensate for this pycnocline deepening. One major source of such turbulence must be the tidal scrubbing at the bottom of the shelf. In any case, the stationarity of the pycnocline does mean that the shear-driven turbulent entrainment in the upper layer corresponding to the above estimate of 10^{-5} m s^{-1} for u_e is actually transporting a heat of about 4.0 MW m^{-1} vertically across the pycnocline.

Thus, even though we are necessarily confined to the extrapolation of entrainment results from the laboratory and the estimates presented here are only educated guesses, these estimates nevertheless suggest that shear-induced mechanical mixing contributes a nonnegligible component to the heat balance at the ice edge. It could be at least as important as the lateral diffusive transport across the ice-edge thermal front and could perhaps be comparable to the double-diffusive transport across the undoubtedly strong pycnocline.

Finally, the authors should be congratulated for demonstrating quantitatively, quite conclusively, what one would have guessed intuitively, but with no substantive support to back it up, namely that the major balance in the heat budget of the mixed layer under the Bering Shelf MIZ is between the heat required to melt the ice and the heat advected onto the ice edge by the warmer waters south of the MIZ.

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